

## Prominence Seismology

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**Abstract.** Given the difficulty in directly determining prominence physical parameters from observations, prominence seismology stands as an alternative method to probe the nature of these structures. We show recent examples of the application of magnetohydrodynamic (MHD) seismology techniques to infer physical parameters in prominence plasmas. They are based on the application of inversion techniques using observed periods, damping times, and plasma flow speeds of prominence thread oscillations. The contribution of *Hinode* to the subject has been of central importance. We show an example based on data obtained with *Hinode*'s Solar Optical Telescope. Observations show an active region limb prominence, composed by a myriad of thin horizontal threads that flow following a path parallel to the photosphere and display synchronous vertical oscillations. The coexistence of waves and flows can be firmly established. By making use of an interpretation based on transverse MHD kink oscillations, a seismological analysis of this event is performed. It is shown that the combination of high quality *Hinode* observations and proper theoretical models allows flows and waves to become two useful characteristics for our understanding of the nature of solar prominences.

## 1. Introduction

Solar prominences are one the most intriguing manifestations of solar activity. These structures consist of large clouds of plasma, two orders of magnitude cooler and denser than the surrounding corona, suspended against gravity by forces thought to be of magnetic origin. The physical properties of prominence plasmas are akin to those of the chromospheric plasma, hence some as yet not well determined mechanisms must provide the required thermal isolation and hydrodynamic support during lifetimes that last from days to weeks. The nature of solar prominences is closely linked to their sub-resolution structuring. Early studies by de Jager (1959) and Kuperus & Tandberg-Hanssen (1967) already pointed out that prominences are composed by many fine threads. This has been confirmed by more recent high-resolution observations obtained by, e.g., Lin et al. (2005). The fine threads are made of cool absorbing material, believed to outline magnetic flux tubes (Martin et al. 2008). Their average width is about  $0''.4$ , their length is in between  $5''$  and  $40''$ , and they have lifetimes of up to 20 minutes.

The measurement of physical properties of prominence plasmas by direct observation is challenging. An alternative to gain knowledge about the physical conditions in prominences is the combined use of observed and theoretical wave properties. The

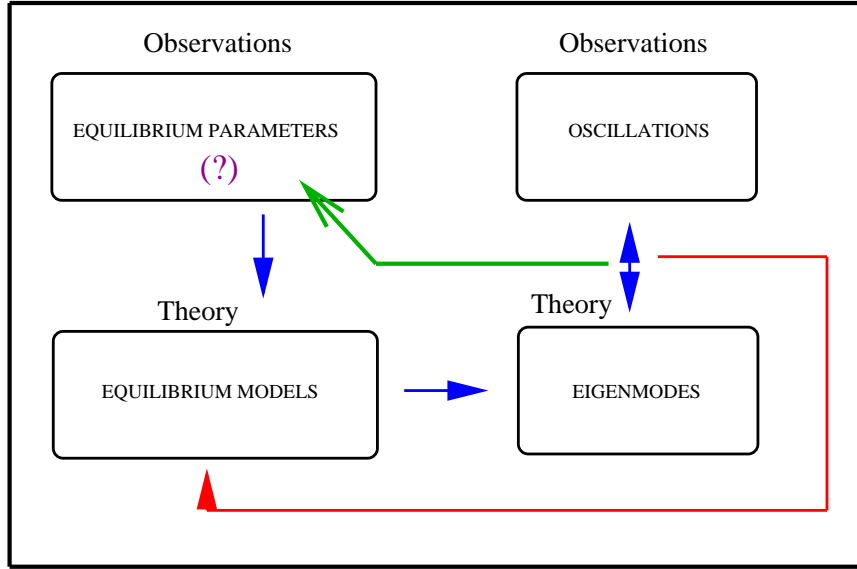


Figure 1. Systematic of MHD seismology.

presence of waves and oscillations in solar prominences is known since a long time (see reviews by Oliver 2009; Ballester 2010). Individual threads or groups of them oscillate with periods that range between 3 and 20 minutes (Yi & Engvold 1991; Yi et al. 1991; Lin et al. 2007; Okamoto et al. 2007; Terradas et al. 2008; Ning et al. 2009; Lin et al. 2009). A recurrently observed property of prominence oscillations is their rapid temporal damping, with perturbations decaying in time-scales of only a few oscillatory periods (see Terradas et al. 2002; Lin 2004; Ning et al. 2009, for recent examples). Another relevant characteristic of waves in solar prominences is the ubiquitous presence of flows (Zirker et al. 1998; Lin et al. 2003, 2005). Flow speeds in the range  $5\text{--}25\text{ km s}^{-1}$  are usually reported in quiescent filament threads, while in active region threads flow speeds of up to  $50\text{ km s}^{-1}$  are detected (Okamoto et al. 2007).

Transverse thread oscillations are commonly interpreted in terms of standing or propagating MHD kink waves. The MHD wave interpretation of thread oscillations has allowed the development of theoretical models (see reviews by Ballester 2005, 2006). Theoretical damping mechanisms have also been developed (see Ballester 2010; Arregui & Ballester 2010, for recent reviews). As information on geometrical properties, damping mechanisms, and flows are incorporated in theoretical models for MHD wave studies, more refined results are obtained that allow a better implementation of prominence seismology.

Solar atmospheric seismology aims to determine physical parameters in magnetic and plasma structures that are difficult to measure by direct means. It is a remote diagnostics method that combines observations of oscillations and waves in magnetic structures, together with theoretical results from the analysis of oscillatory properties of models of those structures. It was first suggested by Uchida (1970) and Roberts et al. (1984), in the coronal context, and by Tandberg-Hanssen (1995) in the prominence context. The systematic of MHD seismology is displayed in Figure 1. Observations of solar coronal magnetic and plasma structures provide us with information from which theo-

retical models about their equilibrium can be constructed. On the other hand, observations also provide us with measurements of certain properties, such as periods, damping times, or flow speeds. By analyzing the wave properties of given theoretical models they can be compared to the observed wave properties. If we find a perfect agreement between observed and theoretical wave properties we can aim to derive some unknown physical parameters of interest. Meanwhile, we can test and improve our models or find constraints. This article discusses three tools for the application of MHD prominence seismology, with an emphasis on the *Hinode* contribution to the area.

## 2. Seismology Using Observed Periods of Thread Oscillations

A recent application of the prominence seismology technique, using the period of observed filament thread transverse oscillations can be found in Lin et al. (2009). These authors find observational evidence about swaying motions of individual filament threads from high resolution observations obtained with the Swedish 1-m Solar Telescope in La Palma. The presence of waves propagating along individual threads was already evident in, e.g., Lin et al. (2007). However, the fact that line-of-sight oscillations are observed in prominences beyond the limb, as well as in filaments against the disk, suggests that the planes of the oscillation may acquire various orientations relative to the local solar reference system. For this reason, Lin et al. (2009) combine simultaneous recordings of motions in the line of sight and in the plane of the sky, which leads to information about the orientation of the oscillatory plane in each case. Periodic oscillatory signals are obtained in a number of threads, that are next fitted to sine curves, from which the period and the amplitude of the waves are derived. The presence of different cuts along the structures allow Lin et al. (2009) to obtain the phase difference between the fitted curves, which can be used to measure the phase velocities of the waves. The overall periods and mean velocity amplitudes that are obtained correspond to short period,  $P \sim 3.6$  minutes, and small amplitude  $\sim 2 \text{ km s}^{-1}$  oscillations. The information obtained from these  $\text{H}\alpha$  filtergrams in the plane of the sky is combined with  $\text{H}\alpha$  Dopplergrams, which allow to detect oscillations in the line-of-sight direction. By combining the observed oscillations in the two orthogonal directions the full vectors are derived, which show that the oscillatory planes are close to the vertical.

Lin et al. (2009) interpret the observed swaying thread oscillations as MHD kink waves supported by the thread body. By assuming the classic one-dimensional, straight, flux tube model a comparison between the observed wave properties and the theoretical prediction can be made in order to obtain the physical parameters of interest, namely the Alfvén speed and the magnetic field strength in the studied threads. To this end the observed phase speed is directly associated to the kink speed, which in the limit of high density contrast, typical of filament plasmas, is simply reduced to  $c_k \simeq \sqrt{2}v_{Ai}$ , with  $v_{Ai}$  the prominence Alfvén speed. This allows to obtain the thread Alfvén speed through  $v_{Ai} \simeq V_{\text{phase}}/\sqrt{2}$ . The obtained values for a set of 10 threads can be found in Table 2 in Lin et al. (2009). Once the Alfvén speed in each thread is determined, the magnetic field strength can be computed, if a given internal density is assumed. For a typical value of  $\rho_i = 5 \times 10^{-11} \text{ kg m}^{-3}$  magnetic field strengths in between 0.9–3.5 G are obtained, for the analyzed events. The important conclusion that we extract from the analysis by Lin et al. (2009) is that prominence seismology is possible and works well, provided high resolution observations are available.

### 3. Seismology Using Observed Periods and Damping Times

The damping of prominence oscillations is a clear feature in many observed events. Lin et al. (2009) show that the amplitudes of the waves passing through two different cuts along a thread are notably different. Among the different damping mechanisms that have been put forward in order to explain the damping of MHD oscillations in prominence plasmas resonant absorption in the Alfvén continuum seems a very plausible one. The mechanism relies on the non-uniformity of the medium in the transverse direction. It was suggested to explain the damping of transverse kink waves in prominence threads by Arregui et al. (2008). The damping of wave modes can be used as an additional source of information about the physical properties of prominence plasmas. In the context of transversely oscillating coronal loops this was done by Arregui et al. (2007) and Goossens et al. (2008). Their analytical and numerical inversion schemes make use of the simple idea that it is the same magnetic structure, whose equilibrium conditions we are interested to assess, that is oscillating with a given period and undergoing a given damping rate. By computing the kink normal mode frequency and damping time as a function of the relevant equilibrium parameters for a one-dimensional model, the period,  $P$  and damping ratio,  $P/\tau_d$ , have the following dependencies

$$P = P(k_z, c, l/a, v_{Ai}), \quad \frac{P}{\tau_d} = \frac{P}{\tau_d}(k_z, c, l/a), \quad (1)$$

with  $v_{Ai}$  the internal Alfvén speed,  $k_z$  the longitudinal wavenumber,  $c = \rho_i/\rho_e$  the density contrast, and  $l/a$  the transverse inhomogeneity length-scale, in units of the tube radius,  $a$ . In the case of coronal loop oscillations, an estimate for  $k_z$  can be obtained directly from the length of the loop and the fact that the fundamental kink mode wavelength is twice this quantity. For filament threads, the wavelength of oscillations needs to be measured. Relations 1 indicate that, if no assumption is made on any of the physical parameters of interest, we have two observed quantities, period and damping time, and three unknowns, density contrast, transverse inhomogeneity length-scale, and Alfvén speed. There are therefore infinite different equilibrium models that can equally well explain the observations. These valid equilibrium models delineate a one-dimensional solution curve in the three-dimensional parameter space  $(c, l/a, v_{Ai})$ . When partially filled threads, with the dense part occupying a length  $L_p$  shorter than the total length of the tube  $L$  are considered, the period and damping time of thread oscillations are seen to depend on  $L_p/L$  (Soler et al. 2010; Arregui et al. 2011). Then, one of such curves is obtained for each value of the length of the thread. The solutions to the inverse problem are shown in Fig. 2a for a set of values for  $L_p$ . It can be appreciated that, even if each curve gives an infinite number of solutions, they define a rather constrained range of values for the thread Alfvén speed. This figure also shows that the ratio  $L_p/L$  is a fundamental parameter in order to perform an accurate seismology of prominence threads. Because of the insensitiveness of the damping ratio with density contrast, for the typically large values of this parameter in prominence plasmas, the obtained solution curves display an asymptotic behavior for large values of  $c$ . This allows us to obtain precise estimates for the filament thread Alfvén speed and the transverse inhomogeneity length scale in that limit for each of the curves. The computation of the magnetic field strength from the obtained seismological curve requires the assumption of a particular value for either the filament or the coronal density. The resulting curves for a typical coronal density and several values of  $L_p/L$  are shown in Figure 2b. As

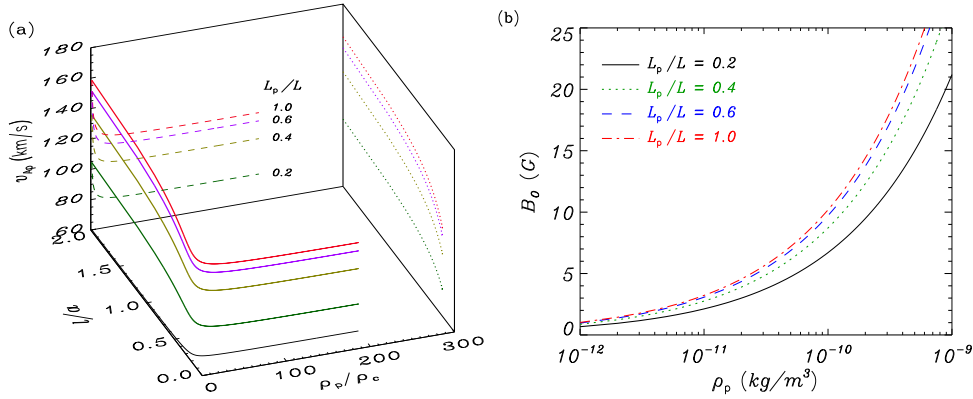


Figure 2. Determination of prominence Alfvén speed (a) and magnetic field strength (b) from the computation of periods and damping times for standing kink oscillations in two-dimensional prominence thread models and observations of period and damping times in transverse thread oscillations. The observed period and damping time are 20 and 60 minutes, respectively, and  $L = 10^5$  km.

can be seen, precise values of the magnetic field strength cannot be obtained, unless the density contrast is accurately known.

#### 4. Seismology of Flowing and Oscillating Prominence Threads

The question of whether propagating disturbances detected in chromospheric and coronal structures are waves or flows has become a hot topic that demands for both observational and theoretical assessment in order to perform an accurate seismology. The contribution of *Hinode* to the subject has been of central importance. Flows constitute an additional source of information about the physical conditions of oscillating structures in conjunction to oscillating periods and damping times. The first seismological application of prominence seismology using *Hinode* observations of flowing and transversely oscillating threads was presented by Terradas et al. (2008), using observations obtained in an active region filament by Okamoto et al. (2007). The observations show a number of threads that flow following a path parallel to the photosphere while they are oscillating in the vertical direction. The relevance of this particular event is in the fact that the coexistence of waves and flows can be firmly established, so there is no ambiguity about the wave or flow character of a given dynamic feature. We have both of them in this particular example. Okamoto et al. (2007) analyze 6 threads and Table 1 displays the relevant measured quantities.

A detailed view of the event analyzed by Okamoto et al. (2007) shows that when a given thread is selected and several cuts along its structure are analyzed as a function of time, oscillations that are synchronous along the entire length of the thread are found. This means that the maximum and minimum amplitudes occur at nearly the same time for all locations. This led Terradas et al. (2008) to interpret these oscillations in terms of the kink mode of a magnetic flux tube.

Let us first neglect the presence of mass flows. By using previous theoretical results from a normal mode analysis in a two-dimensional piecewise filament thread

Table 1. Summary of geometric and wave properties of vertically oscillating flowing threads analyzed by Okamoto et al. (2007).  $2W$  is the thread length,  $v_0$  its horizontal flow velocity,  $P$  the oscillatory period,  $V$  the oscillatory velocity amplitude, and  $H$  the height above the photosphere.

Thread	$2W$ (km)	$v_0$ (km s <sup>-1</sup> )	$P$ (s)	$V$ (km s <sup>-1</sup> )	$H$ (km)
1	3600	39	$174 \pm 25$	16	18 300
2	16 000	15	$240 \pm 30$	15	12 400
3	6700	39	$230 \pm 87$	12	14 700
4	2200	46	$180 \pm 137$	8	19 000
5	3500	45	$135 \pm 21$	9	14 300
6	1700	25	$250 \pm 17$	22	17 200

model by Díaz et al. (2002) and Dymova & Ruderman (2005), Terradas et al. (2008) find that, although it is not possible to univocally determine the physical parameters of interest, a one-to-one relation between the thread Alfvén speed and the coronal Alfvén speed can be established. This relation comes in the form of a number of curves relating the two Alfvén speeds for different values of the length of the magnetic flux tube and the density contrast between the filament and coronal plasma. Figure 3 shows the derived values by changing the length of the tube from bottom to top and the density contrast, from left to right. An interesting property of the obtained curves is that they display an asymptotic behavior for large values of the density contrast, typical of filament to coronal plasmas, and hence a lower limit for the thread Alfvén speed can be obtained. Take for instance thread #6. Considering a length of the total magnetic flux tube of  $L = 100$  Mm, an overall value between 120 and 350 km s<sup>-1</sup> for the thread Alfvén speed is obtained.

Next mass flows are considered. First a simple approximation is made. Consider the form in which mass flow along the cylinder,  $v_0$ , enters in the linear MHD waves equations through the differential operator

$$\frac{\partial}{\partial t} + v_0 \frac{\partial}{\partial z}.$$

The terms coming from the equilibrium flow can, in a first approximation, be ignored because, as noted by Dymova & Ruderman (2005), inside the cylinder the terms with derivatives along the tube are much smaller than those with radial or azimuthal derivatives. By following this approach the problem reduces to solving a time-dependent problem with a varying density profile,  $\rho(z, t)$ , representing a dense part moving along the tube with the flow speed. After solving the two-dimensional wave equations one finds that the flow velocities measured by Okamoto et al. (2007) result in slightly shorter kink mode periods than the ones derived in the absence of flow. Differences are however small and we find period shifts in between 3 and 5%.

Finally, a more complete approach to the problem has been followed by Terradas et al. (2008) who consider the numerical solution of the full MHD wave equations, with no further approximations. The thin tube approximation is not used, the flow is maintained in the equations. Also the density is allowed to change in the simulation as a nonlinear code is used. The full numerical result confirms the previous approximate results regarding the effect of the flow on the obtained periods, and therefore, on the derived Alfvén speed values.

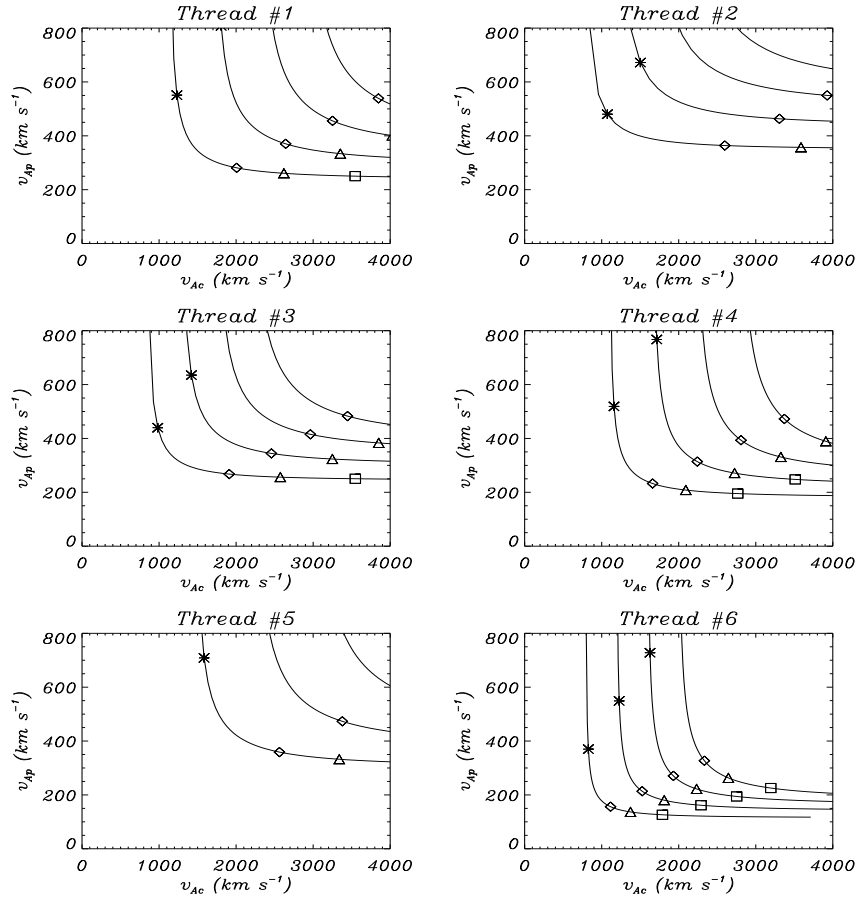


Figure 3. Dependence of the Alfvén velocity in the thread as a function of the coronal Alfvén velocity for the six threads observed by Okamoto et al. (2007). In each panel, from bottom to top, the curves correspond to a length of magnetic field lines of 100 000, 150 000, 200 000, and 250 000 km, respectively. Asterisks, diamonds, triangles, and squares correspond to density ratios of the thread to the coronal gas  $\rho_p/\rho_c \approx 5, 50, 100, 200$ .

## 5. Summary

This paper presents recent developments of the MHD seismology technique applied to prominence plasmas. The combination of refined theoretical models for prominence thread oscillations together with observations allows for the estimation of difficult to measure quantities in these objects. Three complementary techniques for the inversion of physical parameters have been discussed. They make use of the MHD kink wave interpretation for transverse oscillations in filament and active region threads together with observational estimates for quantities such as periods, damping rates, and mass flow speeds. In general, the solution to the inverse problem is unable to provide a single value for all the parameters of interest, since the quantity of unknowns outnumbers that of measured wave properties. However, estimates of physical parameters in a narrow range of values can be derived. A proper further development of prominence seismol-

ogy requires improvements in both theory and observations. Our example using *Hinode* observations demonstrates that high quality observations and proper theoretical analysis allow flows and waves to become two useful characteristics for our understanding of the nature of solar prominences.

**Acknowledgments.** The authors acknowledge the funding provided under the project AYA2006-07637 by Spanish MICINN and FEDER Funds. RS acknowledges a postdoctoral fellowship within the EU research and training network SOLAIRE.

## References

- Arregui, I., Andries, J., Van Doorselaere, T., Goossens, M., & Poedts, S. 2007, *A&A*, 463, 333
- Arregui, I., & Ballester, J. L. 2010, *Space Sci. Rev.*, 59
- Arregui, I., Soler, R., Ballester, J. L., & Wright, A. N. 2011, *A&A*, 533, A60
- Arregui, I., Terradas, J., Oliver, R., & Ballester, J. L. 2008, *ApJ*, 682, L141
- Ballester, J. L. 2005, *Space Sci. Rev.*, 121, 105
- 2006, *Royal Society of London Philosophical Transactions Series A*, 364, 405
- 2010, *Advances in Space Research*, 46, 364
- de Jager, C. 1959, *Handbuch der Physik*, 52, 80
- Díaz, A. J., Oliver, R., & Ballester, J. L. 2002, *ApJ*, 580, 550
- Dymova, M. V., & Ruderman, M. S. 2005, *Solar Phys.*, 229, 79
- Goossens, M., Arregui, I., Ballester, J. L., & Wang, T. J. 2008, *A&A*, 484, 851
- Kuperus, M., & Tandberg-Hanssen, E. 1967, *Solar Phys.*, 2, 39
- Lin, Y. 2004, Ph.D. thesis, University of Oslo, Norway
- Lin, Y., Engvold, O., Rouppe van der Voort, L., Wiik, J. E., & Berger, T. E. 2005, *Solar Phys.*, 226, 239
- Lin, Y., Engvold, O., Rouppe van der Voort, L. H. M., & van Noort, M. 2007, *Solar Phys.*, 246, 65
- Lin, Y., Engvold, O. R., & Wiik, J. E. 2003, *Solar Phys.*, 216, 109
- Lin, Y., Soler, R., Engvold, O., Ballester, J. L., Langangen, Ø., Oliver, R., & Rouppe van der Voort, L. H. M. 2009, *ApJ*, 704, 870
- Martin, S. F., Lin, Y., & Engvold, O. 2008, *Solar Phys.*, 250, 31
- Ning, Z., Cao, W., Okamoto, T. J., Ichimoto, K., & Qu, Z. Q. 2009, *A&A*, 499, 595
- Okamoto, T. J., Tsuneta, S., Berger, T. E., Ichimoto, K., Katsukawa, Y., Lites, B. W., Nagata, S., Shibata, K., Shimizu, T., Shine, R. A., Suematsu, Y., Tarbell, T. D., & Title, A. M. 2007, *Science*, 318, 1577
- Oliver, R. 2009, *Space Sci. Rev.*, 149, 175
- Roberts, B., Edwin, P. M., & Benz, A. O. 1984, *ApJ*, 279, 857
- Soler, R., Arregui, I., Oliver, R., & Ballester, J. L. 2010, *ApJ*, 722, 1778
- Tandberg-Hanssen, E. 1995, *The nature of solar prominences* (Dordrecht: Kluwer Academic Publishers)
- Terradas, J., Arregui, I., Oliver, R., & Ballester, J. L. 2008, *ApJ*, 678, L153
- Terradas, J., Molowny-Horas, R., Wiehr, E., Balthasar, H., Oliver, R., & Ballester, J. L. 2002, *A&A*, 393, 637
- Uchida, Y. 1970, *PASJ*, 22, 341
- Yi, Z., & Engvold, O. 1991, *Solar Phys.*, 134, 275
- Yi, Z., Engvold, O., & Keil, S. L. 1991, *Solar Phys.*, 132, 63
- Zirker, J. B., Engvold, O., & Martin, S. F. 1998, *Nat*, 396, 440